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LCA OF WASTE MANAGEMENT SYSTEMS

Environmental impact and cost assessment of incineration and ethanol production as municipal solid waste management strategies

Mir Abbas Bozorgirad · Hao Zhang · Karl R. Haapala · Ganti S. Murthy

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Abstract
Purpose Municipal solid waste (MSW) can be handled with several traditional management strategies, including landfilling, incineration, and recycling. Ethanol production from MSW is a novel strategy that has been proposed and researched for practical use; however, MSW ethanol plants are not widely applied in practice. Thus, this study has been conducted to analyze and compare the environmental and economic performance of incineration and ethanol production as alternatives to landfilling MSW.
Methods The ISO 14040 life cycle assessment framework is employed to conduct the environmental impact assessment of three different scenarios for the two MSW management strategies based on processing 1 ton of MSW as the functional unit. The first scenario models the process of incinerating MSW and recovering energy in the form of process heat; the second scenario also includes the process of incinerating MSW but yields in the recovery of energy in the form of electricity; and the third scenario models the process of converting MSW into ethanol. The economic impacts of each scenario are then assessed by performing benefit-to-cost ratio (BCR) and net present value (NPV) analyses.
Results and discussion The results from the environmental impact assessment of each scenario reveal that scenario 2 has the highest benefits for resource availability while scenario 3 is shown to be the best alternative to avoid human health and ecosystems diversity impacts. Scenario 1 has the worst environmental performance with respect to each of these environmental endpoint indicators and has net environmental impacts. The results of the economic analysis indicate that the third scenario is the best option with respect to BCR and NPV, followed by scenarios 2 and 1, respectively. Furthermore, environmental and economic analysis results are shown to be sensitive to MSW composition.
Conclusions It appears municipalities should prefer MSW incineration with electricity generation or MSW-to-ethanol conversion over MSW incineration with heat recovery as an alternative to landfilling. The contradiction between the environmental impact assessment results and economic analysis results demonstrates that the decision-making process is sensitive to a broad set of variables. Decisions for a specific MSW management system are subject to facility location and size, MSW composition, energy prices, and governmental policies.

Keywords Cost analysis · Environmental Impact · Ethanol production · Incineration · Life cycle assessment · Municipal solid waste

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M. A. Bozorgirad · H. Zhang · K. R. Haapala (✉)
School of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, 204 Rogers Hall, Corvallis, OR 97331-6001, USA
e-mail: karl.haapala@oregonstate.edu

G. S. Murthy
Department of Biological and Ecological Engineering, Oregon State University, 116 Gilmore Hall, Corvallis, OR 97331-3906, USA

1 Introduction

With the increasing rate of urbanization, not only are urban populations growing but also the rate of waste generation per person is increasing over time. The sharp increase in waste generation from 1.66 (3.66 lbs.) to 2.01 kg (4.43 lbs.) per capita between 1980 and 2010 (EPA 2010), has presented challenges in managing municipal solid waste (MSW) and represents a critical issue for municipalities.

The Mobro 4000 garbage barge which focused public attention on MSW in 1987 is clear evidence to the challenges of increasing waste generation. The barge hauled over 3,100 tons of MSW on a circuitous journey from New York to North Carolina, Alabama, Louisiana, Texas, Mexico, and Belize, where each community refused to accept the malodorous cargo. The barge traveled for about 8 months, until its load was finally incinerated near its origin in Brooklyn, NY and the resulting ash was buried in Islip, NY (Katz 2002).

Landfilling is the most common method of MSW disposal, and accounts for over 50 % of MSW disposal (Fig. 1). According to the US Environmental Protection Agency (EPA), about 136 million tons of MSW were landfilled in 2010 (EPA 2010). The composition of MSW varies in different localities around the world, but environmental disadvantages of this method, however, have resulted in restrictions on its continued use. Many countries have enacted rules to limit the amount of land devoted to landfilling and have set motivating drivers to encourage establishment of new technologies for dealing with disposition of MSW. As a result, many strategies that can considerably reduce the number of landfills and, consequently, decrease the environmental impacts of the waste disposal process have been proposed and developed. These strategies include MSW sorting, gasification, anaerobic digestion, direct incineration, and MSW-derived ethanol production (Cherubini et al. 2009; Kalogo et al. 2007; Murphy and McKeogh 2004; Özeler et al. 2006). These methods need to be investigated in order to identify the most appropriate strategies for different municipalities. Recycling, although not the focus of this study, is a growing alternative strategy, and recovered 34.1 % of 65 million tons of total generated MSW in the USA in 2009 (EPA 2010).

Two of the most important criteria to assist a municipality in the choice of a sustainable waste disposition mechanism are environmental and economic impacts. In this research,

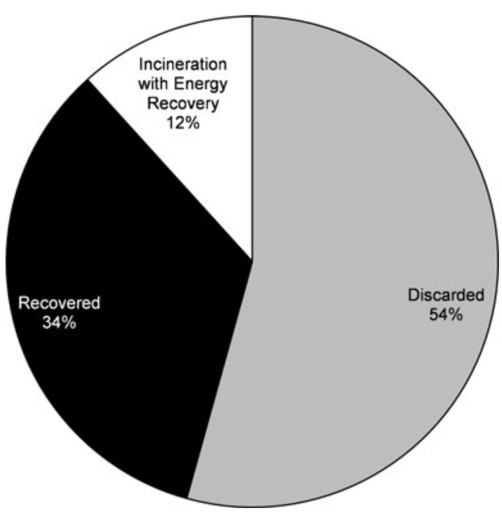

Fig. 1 Management of MSW in the USA, 2010 (EPA 2010)

these criteria are investigated for MSW-derived ethanol production and direct incineration with energy recovery methods for 1 ton of MSW disposal. The primary reason for choosing MSW-derived ethanol production is that this process can produce bioethanol as a co-product which can further mitigate the environmental impacts of the waste disposal process by displacing fossil-based fuels. Additionally, although this option is of interest from both environmental and economic points of view, it has not been widely researched as an alternative MSW management strategy. On the other hand, incineration with energy recovery has been selected as a benchmark for comparison, because this technology is mature and is one of the main alternatives to landfilling.

A review of the related research is presented in the next section to form the background of the study. Thereafter, environmental impacts of the selected methods are investigated, followed by an economic impact assessment. The results of the study are then discussed in order to provide better guidance for choosing between the two methods. Finally, the conclusions of the study are presented.

2 Background

MSW incineration has been studied by many researchers as a viable alternative to landfilling (Al-Salem and Lettieri 2009; Cherubini et al. 2009; Murphy and McKeogh 2004; Ni et al. 2002). Conversely, there are just a few researchers who have considered MSW-to-ethanol production systems as an alternative for MSW management (Kalogo et al. 2007). In this section, a review of the related literature for both of these methods is presented.

2.1 MSW incineration

An incineration plant is usually equipped with energy recovery facilities where energy can be transformed into electricity and/or heat. MSW incineration has been adopted in many countries over the last century as a way to recover energy. It has been reported that the net treatment cost per metric ton of waste incinerated has typically ranged from $25–100 (in 1998) with an average of about $50 (The World Bank 1999). With increasing environmental considerations, however, incineration has been criticized because of resultant toxic gas emissions (Maynard et al. 2010). The large investment and operation and maintenance cost to mitigate emissions have become a concern (Hogg 2002). Al-Salem and Lettieri (2009) studied the costs of three different MSW management scenarios for the state of Kuwait, including collection, transport, and landfilling; direct incineration with energy recovery; and anaerobic digestion. Results from this study show that thermal and biological treatment of MSW results in the lowest cost per individual compared with landfilling.

Cherubini et al. (2009) utilized life cycle assessment (LCA) to compare the environmental impacts of four waste management strategies: a landfill without biogas utilization, a landfill with biogas combustion to generate electricity, a sorting plant that separates the inorganic waste fraction from the organic waste fraction, and a facility to complete direct incineration of waste. The study found the landfill systems to be the most environmentally impactful waste management options while significant environmental savings could be achieved by undertaking energy recovery. Beccali et al. (2001) conducted an LCA comparing landfilling with sorted collection of MSW in Palermo, Italy. Another study (Lo Mastro and Mistretta 2004) compared two different options of MSW collection for thermal treatment in this same locality. Both results showed that sorted collection plays a remarkable role in increasing energy recovery and reducing environmental impact of management systems. Landfilling and incineration with power generation were compared by Ni et al. (2002) using LCA for a waste disposal facility in China. The negative environmental consequences from landfilling were found to be significantly greater than those from incineration with power generation, although the opposite results would be obtained if energy recovery is neglected. In addition, mitigation of environmental impacts through pollutant treatment in the incineration process was found to result in lower impacts than landfilling. Liamsanguan and Gheewala (2007) conducted a study in Thailand that compared landfilling (without energy recovery) and incineration (with energy recovery) using an LCA approach. The results showed that incineration obtained a 59 % reduction in net greenhouse gas emissions of 544 kg CO_2 eq./ton of MSW treated. Landfilling was superior to incineration when methane recovery and electricity production were introduced, however. Chaya and Gheewala (2007) evaluated the environmental impact of incineration and anaerobic digestion in Thailand. Anaerobic digestion was reported to have higher net energy output compared with incineration. Liamsanguan and Gheewala (2008) further compared the environmental impacts of electricity production from a waste incineration plant with those from conventional power plants in Thailand.

From an economic perspective, landfilling is considered as the lowest cost waste management option in most countries (Hogg 2002), and incineration is not a financially competitive alternative due to its high capital and operating costs (EPA of Ireland 2004). MSW incineration requires advanced waste treatment technology which is costly to implement, operate, and maintain. It is estimated that the cost of incineration is an order of magnitude greater than landfilling (The World Bank 1999). The capital costs for an incinerator are dependent on the quality of waste to be processed, the technology employed, and its location. Costs will not only comprise those associated with the purchase of the incinerator plant but also costs for land procurement and preparation prior to build, and indirect costs such as planning, permitting, contractual support, and technical and financial services over the development cycle. According to The World Bank (1999), total capital costs range from \$50–300 million depending on the facility size.

2.2 MSW-derived ethanol production

Conversion of MSW to ethanol has been a focus of research since the 1970s and 1980s when the oil crises prompted the exploration of alternatives for vehicle fuels. Since then, many organizations, including General Motors, Masada Resource Group, RJ Zapata, and Europlasma, have studied new technologies to produce fuels from MSW on a viable scale (Curtiss and Kreider 2009). Two methods that have received the most attention for the conversion of MSW to ethanol are sulfuric acid hydrolysis and enzymatic conversion (Green et al. 1988; Cardona and Sánchez 2007; Curtiss and Kreider 2009).

Besides the technical aspects of converting biomaterial to ethanol (Green et al. 1988; Li and Kraslawski 2004; Olsson and Hahn-Hägerdal 1996; Westerberg 2004), there are few reports that address the environmental and economic aspects of this method of ethanol production. The environmental impacts of converting MSW to ethanol have been considered from two different points of view: MSW-derived ethanol as an automobile fuel and conversion to ethanol as a method of MSW disposal. Sharp increases in prices of fossil fuels have directed much attention to biofuels, including ethanol. Ethanol can be derived from nearly all plant-based materials, because they contain sugars that can be fermented to ethanol (US DOE 2012a).

In contrast to first-generation biofuels, such as corn ethanol, second-generation biofuels use nonfood feedstocks such as agricultural residues and dedicated energy crops (Festel 2008; Li and Khraisheh 2010). MSW is one potential feedstock due to its low cost, consistent supply, and existing collection infrastructure. The proportion of MSW that can be used for ethanol production depends on the composition of MSW, and this composition varies from one urban district to another. According to several reports, however, MSW is composed of 50 to 60 % organic materials that can be used for bioethanol production (Kalogo et al. 2007; Schmitt et al. 2012).

Kalogo et al. (2007) conducted an LCA study to compare the environmental impacts of MSW-derived ethanol with the impacts of gasoline, corn ethanol, and crop-cellulosic ethanol. They also compared these impacts with the environmental impacts of landfilling of MSW. As a result, it was found that MSW ethanol used as E85 (blended with 15 % gasoline) reduces GHG emissions by 65 and 58 % compared with gasoline and corn ethanol, respectively. Performance compared with crop-cellulosic ethanol, however, depends on whether

MSW classification is considered (MSW classification, or sorting, results in a lower performance due to the additional processing). It was reported that converting MSW to ethanol results in the saving of 397–1830 MJ fossil energy per metric ton of MSW, while landfilling results in the consumption of 177–577 MJ fossil energy per metric ton of MSW. They modeled their analysis on the gravity pressure vessel (GPV) process developed by GeneSyst (GeneSyst 2012). This process was also examined by Zhang et al. (2010) who studied different feedstocks and conversion pathways for ethanol to assess the feasibility of California's low carbon fuel standard. Their study used LCA to evaluate the environmental implications of converting MSW and other feedstocks to ethanol. Furthermore, they performed a financial analysis and provided the minimum selling price for ethanol obtained from each of these feedstocks.

Chester and Martin (2009) assessed the production potential of ethanol from MSW in the state of California. They analyzed cost, energy, and GHG emissions resulting from converting MSW to ethanol based on the dilute acid process developed by the US National Renewable Energy Laboratory (NREL) (Aden et al. 2002). Schmitt et al. (2012) also used NREL's model as their basis to develop a model for a lignocellulosic biorefinery. They assessed technical and environmental aspects of converting three different lignocellulosic resources into ethanol, i.e., MSW, low-grade mixed waste paper, and organic yard waste. Their results showed high conversion rates for all three resources. They also performed an LCA study on the waste-to-ethanol conversion process. Although the environmental impacts of this conversion process are highly dependent on the technology and the process conditions, the results of this study revealed that producing biofuel from waste has lower impacts compared with the current ethanol technologies.

LCA has been successfully utilized in the field of solid waste management to assess differences in environmental performance among different waste treatment strategies and related activities. However, there have not been many studies comparing an MSW management system producing energy from incineration to MSW-ethanol production. As discussed above, research has shown that both incineration and MSW-ethanol production have environmental merit compared with a conventional landfill. The study reported herein assesses the environmental loads of energy production from incineration and ethanol production from MSW. The objective is to assess the environmental and economic performance of energy from MSW incineration and ethanol production.

3 Environmental impact assessment

The ISO 14040 LCA framework is utilized to conduct the environmental impact assessment in this study (Rebitzer et al. 2004). In this section, the environmental impacts of three different MSW management strategies are assessed. Scenario 1 is the process of incinerating MSW and recovering energy as process heat, scenario 2 is the process of incinerating MSW and recovering energy as electricity, and scenario 3 is the process of converting MSW into ethanol. For scenarios 1 and 2, the incineration processes are the same while the energy-generation methods are different.

3.1 Goal and scope definition

The goal of this study is to assess environmental and economic performance of three MSW management strategies as an alternative to landfilling. This study will provide a reference to practitioners of potential impacts of alternative energy recovery options. The three alternatives investigated are incineration with heat recovery, incineration with electricity recovery, and ethanol production from MSW. The functional unit is 1 ton of MSW delivered to the reprocessing plant. In this study, incineration and ethanol production systems are assumed to first manage MSW of the same assumed composition, i.e., 42 % paper, 31 % food, 10 % yard, 9 % plastic, 5 % metal, and 3 % miscellaneous. These data represent the average MSW composition for the city of Canton, Ohio (GeneSyst 2012). Later, three alternative MSW compositions are considered. It is assumed that MSW feedstock is classified before it is placed into the treatment system. Therefore, heavy materials such as glass, sand, and copper wire are separated from the MSW, and the residual, referred to as MSW fluff, is considered the main input for all three scenarios. Environmental impacts are analyzed for each of the systems, including materials and energy involved in the processes and facilities, using the ReCiPe 2008 impact assessment method as described in section 3.3. The system boundaries for each scenario are described in the following sections.

3.1.1 Incineration scenarios and system boundary

A modern incinerator is a complex industrial processing plant involving several process steps in order to optimize energy production and unwanted emissions. The processing plant can be divided into several subplants of which the most important are the combustion chamber, where the solid material is combusted; the after-combustion chamber, where the gases from the combustion chamber are held at high temperature in the presence of excess oxygen in order to oxidize unburned gases; the boiler, which recovers the energy from the exiting hot flue gases; the flue gas cleaning system, an optional water treatment system for cleaning of wet flue gas; and an ash handling system, where the ash and slag are collected for disposal in a landfill. The organic matter is oxidized primarily to CO_2 and H_2O, which is discharged to the atmosphere. Noncombustible, inorganic matter is discharged as slag or ash. The process also produces

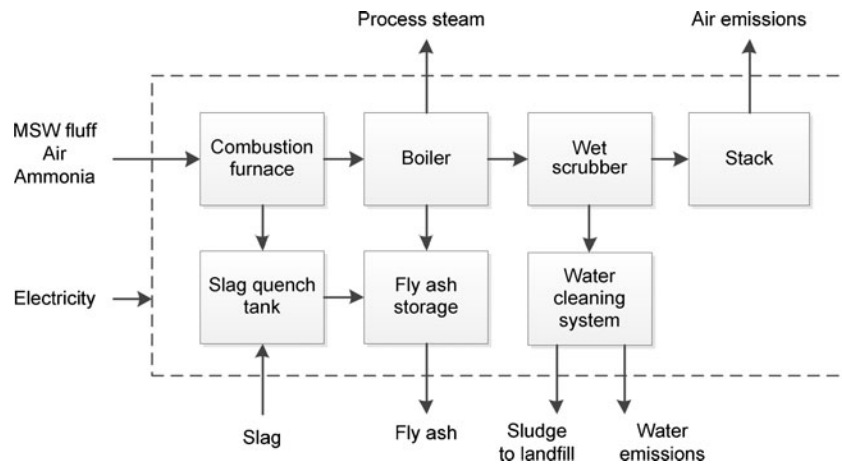

Fig. 2 Scenario 1 system boundary (MSW incineration with heat recovery)

unwanted emissions, such as nitrogen oxides, sulfur oxides, hydrochloric acid, heavy metals, polyaromatic hydrocarbons, and chlorinated organic compounds (Sundqvist 1999). The energy generated during combustion can be used for steam production, district heating, and production of electricity. In this study, two energy recovery strategies are investigated, with one producing heat (scenario 1), and the other producing electricity (scenario 2). The processing plants for each scenario are assumed to be the same, except scenario 2 has an additional electricity generation system composed of a turbine and a generator (Fig. 3). The system boundaries for scenarios 1 and 2 are depicted in Figs. 2 and 3, respectively.

3.1.2 Ethanol production scenario and system boundary

The GPV process, developed by GeneSyst (Kalogo et al. 2007; GeneSyst 2012), was used to model the MSW-to-ethanol conversion; this process was developed and tested specifically for MSW. At the heart of the GPV is a long pipe that is drilled into the earth. A mixture of MSW and water is directed downward to the bottom of the pipe, and then back up to the surface. The principle behind this technology is that the liquid water at the bottom of the pipe is at high pressure and temperature and can dissolve almost any organic chemical. The dissolved organics are transformed to the desired end product by introducing carbon dioxide into the GPV (which forms carbonic acid), in the presence of sulfuric acid or a catalyst.

The details of the process employed by GPV for treating MSW are represented in Fig. 4. MSW fluff is first shredded into small pieces. The mixture of MSW fluff and water is then directed through a continuous dilute acid hydrolysis process under high pressure (62 bar) and high temperature (260–280 °C) conditions to convert the cellulosic material into sugar. A fermentation process then converts this sugar into low-concentration ethanol, and a subsequent distillation process refines this ethanol to obtain fuel-quality ethanol. The system boundary for this scenario is shown in Fig. 4.

3.2 Life cycle inventory

The incineration scenarios are adapted from a prior study conducted by Sundqvist (1999) who analyzed an incineration plant in Sweden. Referring to the system boundaries shown in Figs. 2 and 3, inputs include components of MSW; $CaCO_3$ for reducing the concentration of sulfur dioxide and hydrochloric acid; ammonia for reduction of NO_x; energy; and the incineration plant infrastructure. Outputs include emissions to air, slag,

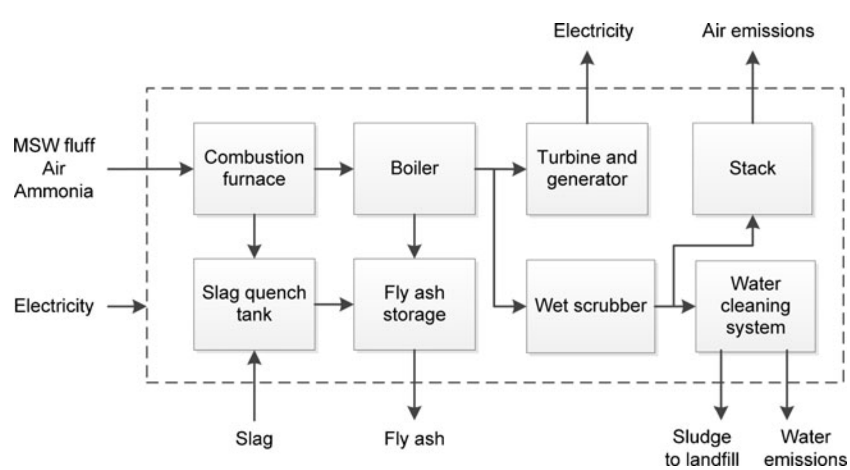

Fig. 3 Scenario 2 system boundary (MSW incineration with electricity generation)

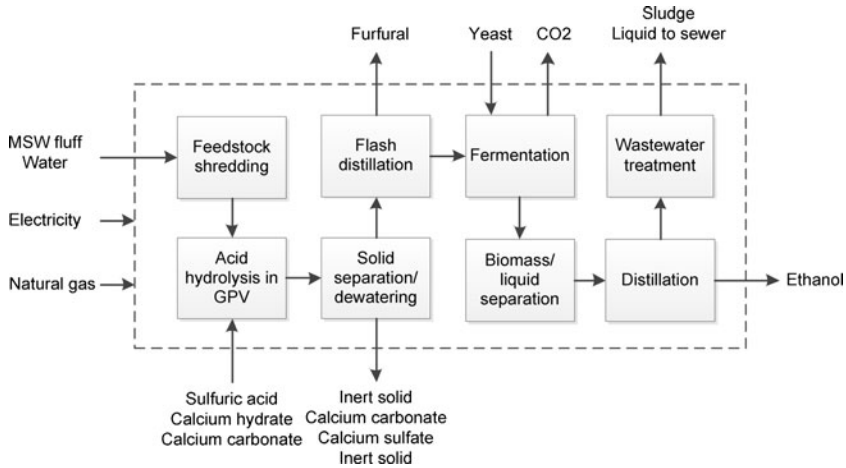

Fig. 4 Scenario 3 system boundary (ethanol production from MSW)

and ash, and energy outputs. Specific quantities are reported in Table 1.

The main inputs and outputs to the process of converting MSW into ethanol using GPV are presented in Table 2. The reported data are the overall inputs and outputs to the entire conversion process and not the material usage and energy consumption of each of the individual processes. Quantities were determined using a spreadsheet model developed as a part of this research, based on the process developed by Genesyst.

3.3 Environmental impact assessment

To determine environmental impacts of the waste management strategies evaluated, the ReCiPe 2008 method with World ReCiPe H/A weighting is selected, because of its categorization of impacts (Goedkoop et al. 2009). The impact categories are addressed at both the midpoint level, with 18 indicators, and the endpoint level, with three indicators (damage to human health, damage to ecosystems diversity, and damage to resource availability). In this research, the hierarchist perspective is applied, which is based on the most common policy principles with regard to time frame and other issues (Goedkoop et al. 2009). LCI data were imported to LCA software (SimaPro 7.3), which generated the relative environmental impact results shown in Table 3 and Fig. 5. Midpoint impact categories were aggregated into the three endpoint indicators which are shown in Fig. 6.

From the endpoint perspective, incineration with electricity generation (scenario 2) has the greatest resource availability benefits, due to avoided fossil fuels use. Ethanol production (scenario 3) has the most benefits in terms of ecosystems diversity, while incineration with heat recovery (scenario 1) causes the highest impact on ecosystems diversity. With respect to human health, scenario 3 has more benefits not only because this scenario has low emissions to the air, but also because the output, ethanol, will displace gasoline and other fossil fuels (Kalogo et al. 2007). Incineration can impact human health, because of the emissions that are released into the air; however, this analysis demonstrates that the production of electricity

Table 1 Incineration system inputs and outputs per ton of MSW (Sundqvist 1999)

Inputs	Amount	Unit	Outputs	Amount	Unit
MSW	1.0	T	CO_2	1.1	T
NH_3	1.3	kg	SO_2	393.0	G
$CaCO_3$	22.0	kg	HCl	177.0	g
C	290.0	kg	Dust	15.0	g
H	49.0	kg	CO	1,790.0	G
S	2.6	kg	PAH	11.0	mg
N	7.0	kg	Dioxin	3.0	µg
Cl	5.0	kg	NO_x	852.0	G
Ash	217.0	kg	Fly ash	31.5	kg
Electrical energy	69.0	kWh	Slag	114.0	kg
Scenario 1			Heat	3.07	MWh
Scenario 2			Electricity	0.98	MWh

MSW municipal solid waste, *PAH* polyaromatic hydrocarbons

Table 2 Ethanol conversion inputs and outputs per ton of MSW (GeneSyst 2012)

Input	Amount	Unit	Output	Amount	Unit
MSW fluff	1.00	t	Inert solids	49.11	kg
Water	203.45	L	Water	234.69	L
Sulfuric acid	19.17	kg	Calcium sulfate	29.65	kg
Calcium hydroxide	31.89	kg	Calcium carbonate	21.62	kg
Calcium carbonate	1.56	kg	Furfural	9.01	kg
Yeast	10.81	kg	Yeast	10.76	kg
Electricity	0.027	MWh	CO_2	47.57	kg
Natural gas	0.23	MWh	Ethanol	87.69	L
			Sludge	1.85	kg
			BOD	8.60	µg

Table 3 Relative environmental impacts of each MSW management strategy

Impact category	Scenario 1 (%)	Scenario 2 (%)	Scenario 3 (%)
Climate change, human health	100.00	61.10	−87.96
Ozone depletion	−100.00	−80.81	−93.12
Human toxicity	−35.11	−100.00	−15.85
Photochemical oxidant formation	0.56	−100.00	−6.36
Particulate matter formation	−19.99	−100.00	−7.37
Ionising radiation	−30.26	−100.00	−5.58
Climate change, ecosystems	100.00	61.03	−87.83
Terrestrial acidification	−23.37	−100.00	−7.31
Freshwater eutrophication	−3.03	−9.01	−100.00
Terrestrial ecotoxicity	−1.47	−3.53	−100.00
Freshwater ecotoxicity	−14.70	−45.98	−100.00
Marine ecotoxicity	−41.45	−100.00	−61.74
Agricultural land occupation	−1.01	−2.79	−100.00
Urban land occupation	−38.15	−75.17	−100.00
Natural land transformation	−100.00	−99.84	−78.25
Metal depletion	−100.00	−55.06	−74.14
Fossil depletion	−49.34	−100.00	−10.10

ReCiPe Endpoint (H) V1.03/ World ReCiPe H/A

(scenario 2) can compensate for the negative impacts from those emissions.

3.4 Interpretation

The results of LCA studies are mainly affected by several sources of uncertainty related to the methodological choices or initial assumptions made on allocation rules, system boundaries, and the quality of the data (Cellura et al. 2011). One of the main sources of these uncertainties is the use of secondary data. These data are basically obtained from referenced literature, and contribute a large amount of uncertainty to the study, mainly because of their unknown accuracy, reliability, and collection method. One of the proposed procedures to estimate the effects of these uncertainties on the result of an LCA study is to perform sensitivity analysis on the uncertain parameters. In this study, the system boundaries are defined by the researchers, and the allocation rules, based on the mass of materials, are determined by the LCA software (SimaPro 7.3). A sensitivity analysis is conducted to estimate the effects of different MSW compositions on the LCA results. Four cases are considered for different compositions of MSW: case 1, MSW Canton, Ohio (GeneSyst 2012); case 2, MSW US Average (EPA 2010); case 3, MSW Europe Average (Cherubini et al. 2009); and case 4, Thailand Average (Chaya and Gheewala 2007). Table 4 represents different compositions of MSW for each of these cases. It is worth noting that this research is based on US available information, thus the last two cases are considered as variations of MSW compositions. The LCA results for these cases

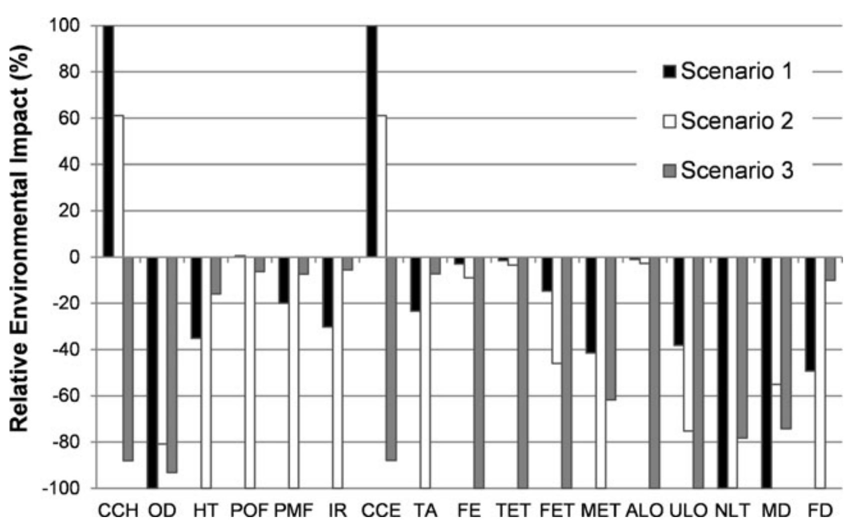

Fig. 5 Relative environmental midpoint impacts for each MSW management strategy (method: ReCiPe Endpoint (H) V1.03/World ReCiPe H/A)

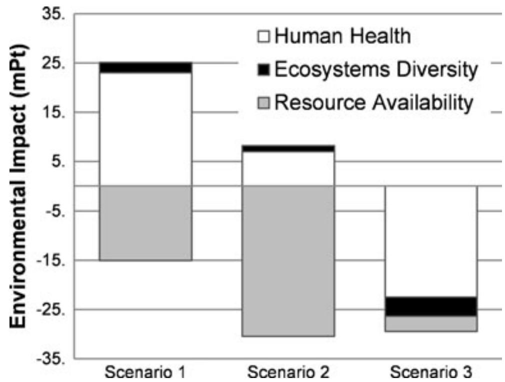

Fig. 6 Environmental endpoint impacts for each MSW management strategy (method: ReCiPe Endpoint (H) V1.03/World ReCiPe H/A)

are reported in Table 5 in terms of the endpoint indicators using the ReCiPe 2008 method. It can be seen that scenario 3 is the best option for each case with respect to human health and ecosystems diversity, followed by scenarios 2 and 1, respectively. With respect to resource availability, scenario 1 is the best option for each case, followed by scenarios 1 and 3, respectively.

4 Economic impact assessment

In this section, the details of costs and sales for a 500 ton/day MSW incineration plant, as well as a 500-ton/day MSW-ethanol plant are provided as a basis for economic impact assessment of these two systems. The 500-ton/day plant is a medium size plant which has been studied by several researchers (Cheng and Hu 2010; GeneSyst 2012; Sakamoto 2004; The World Bank 1999). Furthermore, a cost–benefit analysis is conducted to compare the economics of these systems.

4.1 Costs and benefits of incineration

The costs of an incineration plant can be categorized into investment costs, operating costs, and the maintenance costs. The actual investment cost for a waste incineration plant depends on a wide range of factors, especially the size (capacity) of the plant and the calorific value of the waste (The World Bank 1999). Operating costs are composed of fixed operating costs, which include cost of administration and salaries, and variable operating costs, which include cost of chemicals for the flue gas cleaning system, cost of electricity, cost of water and handling of wastewater, and cost of residue disposal. Maintenance costs include all the costs associated with the maintenance of machinery and buildings.

Table 4 Cases selected for MSW compositions

MSW compositions (%)	Case 1	Case 2	Case 3	Case 4
Paper/paper board	42.0	28.5	18.8	20.70
Food/kitchen	31.0	13.9	49.5	35.94
Wood/textile/yard	10.0	19.8	3.7	8.48
Plastic/rubber/leather	9.0	20.8	23.5	18.32
Metal	5.0	9.0	2.8	3.75
Others	3.0	8.0	1.7	12.81

Table 5 Sensitivity analysis of environmental impacts for different MSW compositions

Impact (mPt)	Case 1	Case 2	Case 3	Case 4
Human health				
Scenario 1	23.0	21.1	24.6	22.6
Scenario 2	7.0	0.0	5.9	4.9
Scenario 3	−23.0	−20.0	−21.0	−8.0
Ecosystems diversity				
Scenario 1	2.1	2.0	2.3	2.1
Scenario 2	1.2	0.7	1.2	1.1
Scenario 3	−4.0	−3.0	−4.0	−2.0
Resources availability				
Scenario 1	−15.0	−19.0	−18.0	−17.0
Scenario 2	−30.0	−40.0	−36.0	−34.0
Scenario 3	−3.0	−1.0	−2.0	−5.0

ReCiPe Endpoint (H) V1.03/World ReCiPe H/A

Economic benefits of an incineration plant mainly include the sales of energy (heat/electricity) and the income obtained from disposing MSW. In an ideal situation, the income from energy sales can cover up to 80-90 % of total costs. The potential energy production and, consequently, the income from the sale of this energy depends heavily on the energy content (net calorific value) of the waste. Waste management facilities have a price for collecting and handling of garbage, called a tipping fee, which varies between $20–120/ton of MSW and is dependent on the facility location (Kalogo et al. 2007; Sakamoto 2004). An average of $55 is assumed for this fee in this study, and analysis is based on 312 working days/year (Sakamoto 2004). Tables 6 and 7 summarize all the data related to the costs and benefits of an MSW incineration plant, respectively. All these data are converted to values in 2012 USD (US Department of Labor 2012).

4.2 Costs and benefits of MSW-derived ethanol production

The costs of an MSW-to-ethanol plant are similar to those for an MSW incineration plant. Sakamoto (2004) studied the financial feasibility of a 500-ton/day ethanol plant based on a pilot plant developed by GeneSyst, which was adopted in this analysis. These data are shown in Table 6.

Table 6 Expenditures for each MSW management strategy

Cost category	Amount (10^6 USD)	Period
Capital (scenario 1)[a]	90.55	First year
Capital (scenario 2)[a]	110.36	First year
Capital (scenario 3)[b]	24.38	First year
Plant operation and overhead costs (scenarios 1 and 2)	3.44	Annually
Plant operation and overhead costs (scenario 3)	3.97	Annually
Disposal of residues (scenarios 1 and 2)	0.68	Annually
Disposal of residues (scenario 3)	0.61	Annually
Maintenance (scenario 1)	1.29	Annually
Maintenance (scenario 2)	2.06	Annually
Maintenance (scenario 3)	1.98	Annually
Disposal/reuse of bottom ash (scenarios 1 and 2)	0.27	Annually
Total costs (scenario 1)	5.68	Annually
Total costs (scenario 2)	6.45	Annually
Total costs (scenario 3)	6.56	Annually

All data converted to 2012 USD (US Department of Labor 2012)

[a] The price is obtained from Holstein (2010)

[c] The price is obtained from The World Bank (1999)

The benefits of such a production system include three main sources of income: sales of ethanol, sales of chemical by-products, and income from disposing of MSW. Unlike production of ethanol from corn starch or other cellulosic biomass, the feedstock itself is a remarkable source of income that comprises over 30 % of total annual sales as shown in Table 8. It may be worth noting that sales of recycled materials and government subsidies have not been considered because of the wide variation in their values and their low contribution to total income (less than 10 %). Furthermore, these sources of revenue are considered for all three waste management strategies to ensure balanced comparison among the scenarios.

Table 7 Income data for an MSW incineration plant

Income source	MSW energy (MWh/ton)	Unit	Price (USD)	Annual amount (10^6 USD)
Heat (scenario 1)	3.07	MWh	15.00[a]	7.19
Electricity (scenario 2)	0.98	MWh	87.38[b]	13.32
Feedstock (scenarios 1 and 2)				6.44
Total income (scenario 1)				13.63
Total income (scenario 2)				19.76

All data converted to 2012 USD (US Department of Labor 2012)

[a] The price is obtained from Holstein (2010)

[b] The price is obtained from The World Bank (1999)

Table 8 Income data of ethanol production from MSW

Income source	Yield (USD/ton MSW)	Unit	Price (USD)	Annual amount (10^6 USD)
Ethanol	87.69[a]	L	0.62	8.48
$CaSO_4$	30.00[b]	kg	0.01	0.05
Feedstock				6.44
Total				14.97

[a] Price obtained from US (2012b)

[b] Price obtained from ICIS (2012)

4.3 Cost–benefit analysis

To perform a cost–benefit analysis, all sources of cost and income must be determined; such approaches have been reported, e.g., Lo Mastro and Mistretta (2006). The main costs (Table 6) include capital cost (C_c), operation cost (C_o), residue cost (C_r), and maintenance cost (C_m). The main sources of income (Table 7) include product sales (I_p) where the product can be either heat or electricity and income from management of the MSW, referred to as feedstock (I_f). Assuming a lifetime of 20 years and an interest rate (i_r) of 3.375 %, the average of interest rates for the last 20 years from the Board of Governors of the Federal Reserve (2012), a benefit-to-cost ratio (BCR) and a net present value (NPV) is obtained for each of the scenarios based on the following equations:

$$\mathrm{BCR} = \frac{\sum_{t=1}^{20} \frac{I_{total}}{(1+i_r)^t}}{\sum_{t=1}^{20} \frac{I_{total}}{(1+i_r)^t}}$$

$$\mathrm{NPV} = \sum_{t=1}^{20} \frac{I_{total} - C_{total}}{(1+i_r)^t}$$

where $C_{total}=C_c+C_o+C_r+C_m$, and $I_{total}=I_p+C_f$

Producing ethanol from MSW (scenario 3) was found to have the highest BCR of 1.81 (scenario 1 was 1.14 and scenario 2 was 1.40). The NPV is estimated to be 23, 78, and

Table 9 Economic analysis for different compositions of MSW

Scenario	Case 1	Case 2	Case 3	Case 4
BCR				
1	1.14	1.30	1.25	1.20
2	1.40	1.60	1.57	1.50
3	1.81	1.55	1.68	1.59
NPV (10^6 USD)				
1	23	50	41	33
2	78	134	112	97
3	93	64	78	68

MSW municipal solid waste, *BCR* benefit-to-cost ratio, *NPV* net present value

93 million dollars for scenarios 1, 2, and 3, respectively. Table 9 reports the values of BCR and NPV for each composition of MSW studied, which are indicated in Table 4. As can be seen from Table 9, the economic attractiveness of the three scenarios is impacted by the MSW composition. In case 2, scenario 2 is the best option with respect to both BCR and NPV, and for the other two cases, scenario 2 results in the best NPV while scenario 3 remains the best option with respect to BCR.

5 Discussion

In this research, three different strategies for MSW management have been evaluated with respect to environmental and economic performance. The results from the environmental LCA indicated that scenario 3 (ethanol production) has the highest benefits for human health and ecosystems diversity, while scenario 1 (heat recovery from incineration) showed the worst impacts with regard to these endpoint indicators. Scenario 2 (electricity generation from incineration) was determined as the best option to avoid resource depletion, followed by scenarios 1 and 3, respectively. A sensitivity analysis revealed that these conclusions are robust to slight changes in MSW composition. More drastic variations in the fermentable portion of MSW, however, would most likely effect environmental impact results. From an economic point of view, scenario 3 was found to have the highest BCR and NPV. Nevertheless, economic results are sensitive to MSW composition, such that scenario 2 seems more appealing for particular MSW compositions.

6 Conclusions

The objective of this research was to compare the environmental and economic aspects of three MSW management strategies. Practitioners who must consider ethanol production from MSW and incineration of MSW are provided with a reference to assess the potential impacts of the two systems and alternative energy recovery options based on information gathered from the literature. For the scenarios and cases examined, it was found that environmentally and economically preferential options can be in agreement or disagreement, depending on the assumptions made. Thus, the results for a specific system design must be subject to examination of the effect of facility location and size, MSW composition, energy prices, and governmental policies. It can be reiterated that practitioners must consider a broad set of factors when making an MSW management system decision, including environmental impacts, economic effects, and social issues.

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